

Nondestructive Evaluation Aerospace Composites

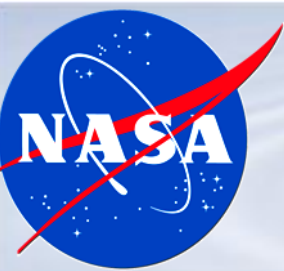
**Dr. Cara Leckey, Elliott Cramer, Daniel Perey
Nondestructive Evaluation Sciences Branch
NASA Langley Research Center**



Outline

Nondestructive Evaluation Sciences Branch

- National Aeronautics and Space Administration (NASA)
- NESB Overview
- Need for NDE of Composites
- NESB NDE Composites Research
- Conclusion



NASA Locations

Nondestructive Evaluation Sciences Branch

- NASA
- NESB
- Need for composites NDE
- NESB Research
- Conclusion

14 Major Centers/Facilities
~18,000 Civil Service Employees
~40,000 Contract Employees



Centers:

- Ames Research Center
- Armstrong Flight Research Center
- Glenn Research Center
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Johnson Space Center
- Kennedy Space Center
- Langley Research Center
- Marshall Space Flight Center
- NASA Headquarters
- Stennis Space Center
- Wallops Flight Facility



NASA Langley Research Center

Nondestructive Evaluation Sciences Branch



Since 1917

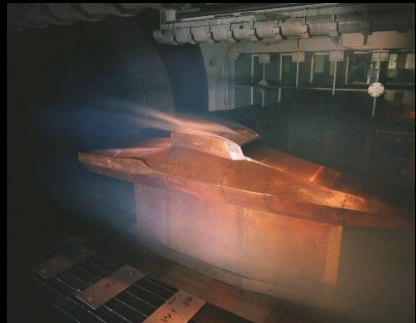


A picture from 1934 that includes Charles Lindbergh, Howard Hughes, Glenn Curtiss and Orville Wright is an indicator of the history of LaRC.



Alan Shepard At Lunar Landing Research Facility
NASA Langley Research Center 3/30/1970 Image # EL-1996-00219

A picture from 1970 of Alan Shepard (1st American in space) at LaRC lunar landing facility.



Supersonic
vehicles



More efficient vehicles



Autonomous vehicles



Aeronautics Research

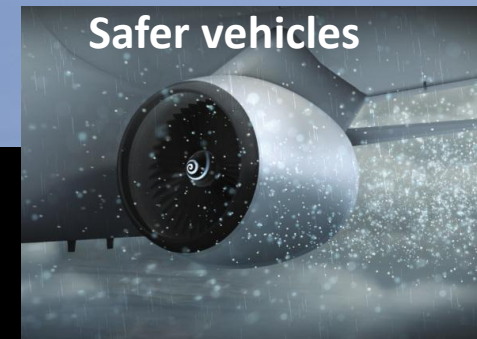
Personal Air
Vehicles



Air traffic



Safer vehicles



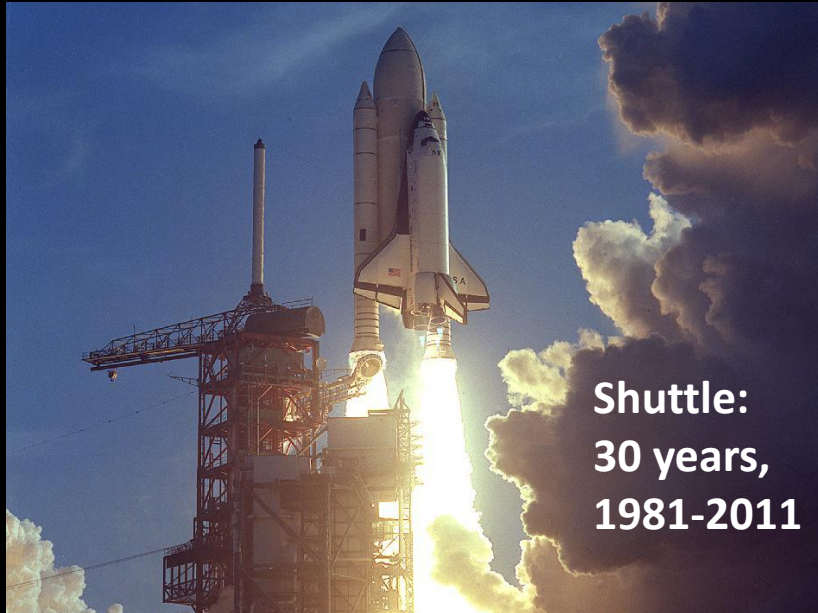


Commercial
Crew to ISS



Space Launch System (SLS)
Beyond LEO
Asteroid, Mars

Human Exploration



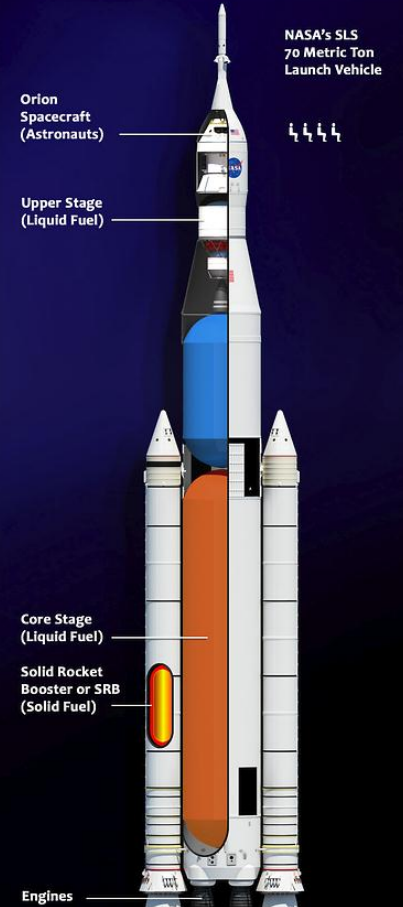
If you wonder how NASA's Space Launch System, or SLS, compares to earlier generations of NASA launch vehicles...



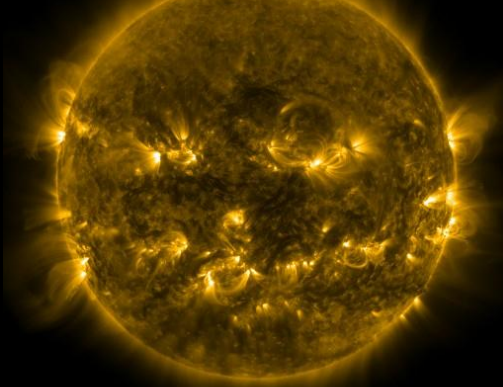
SLS will produce 8% more thrust at launch than the space shuttle and 12% more than the Saturn V.



SLS will launch more than three times as much weight into space as the space shuttle.



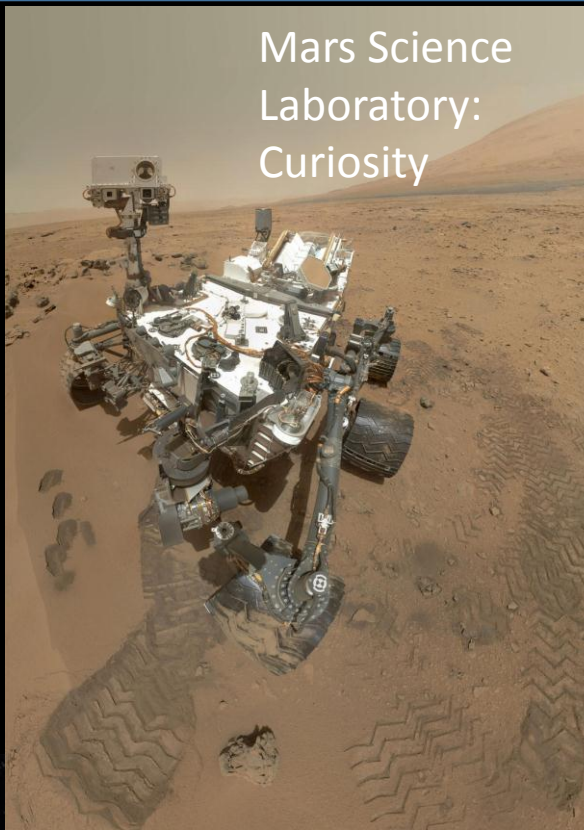
Heliophysics: SDO



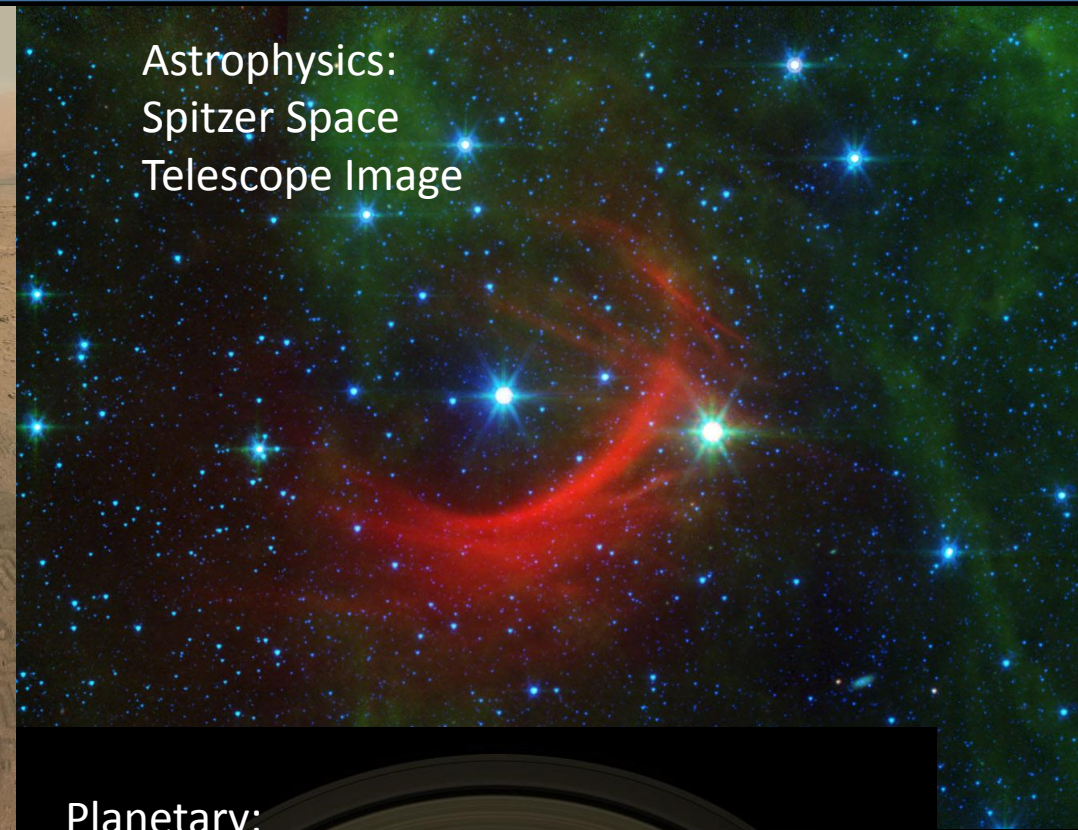
SDO/AIA 171 2014-10-08 17:11:12 UT

Science

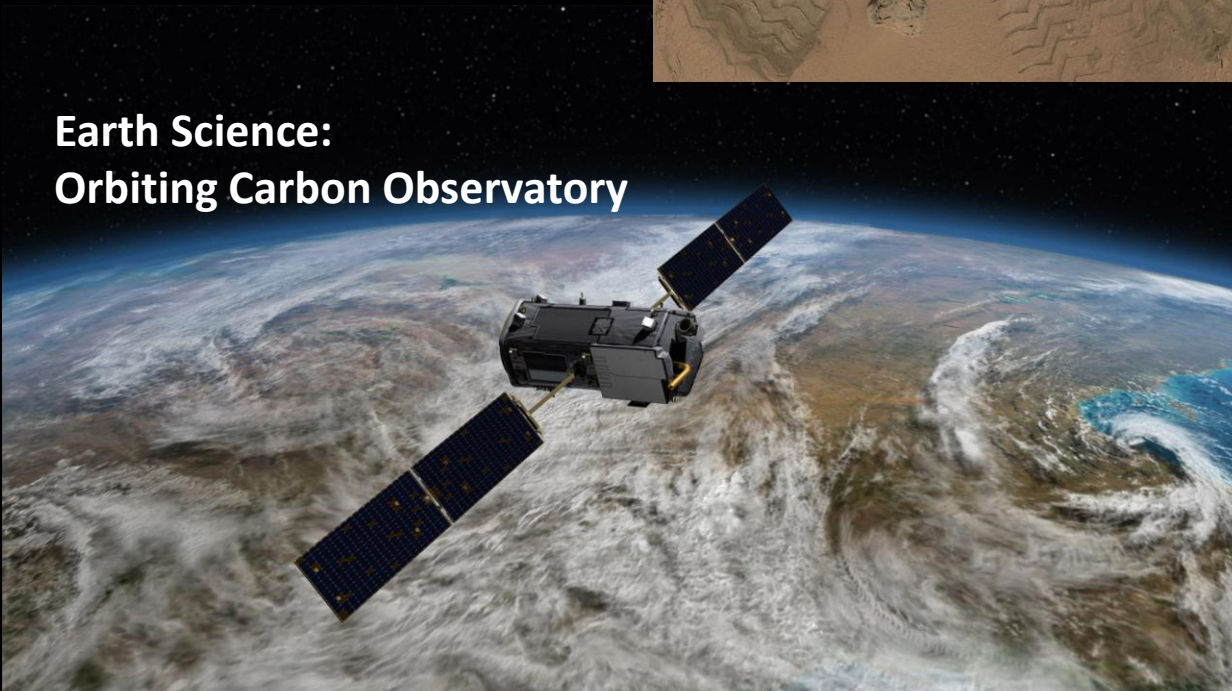
Mars Science
Laboratory:
Curiosity



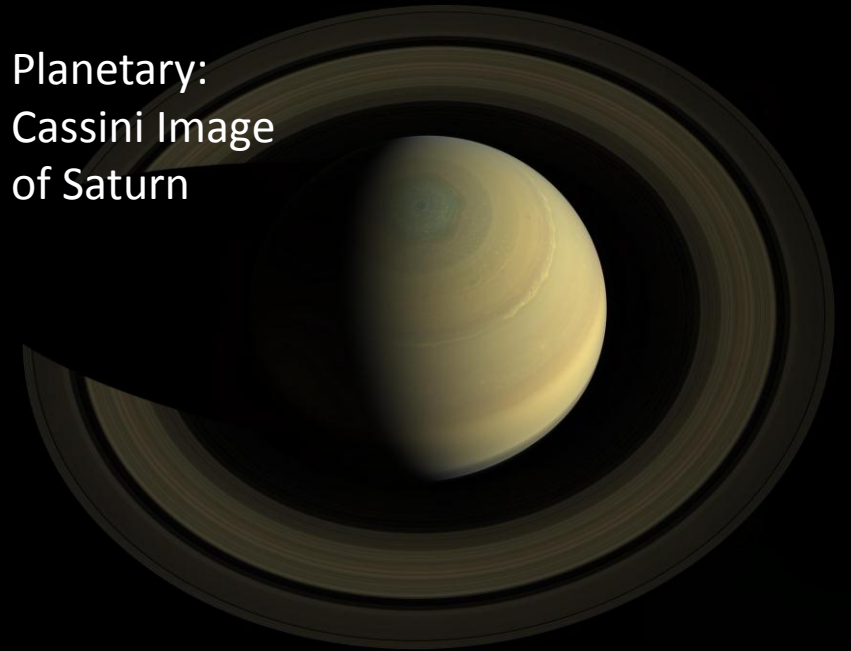
Astrophysics:
Spitzer Space
Telescope Image

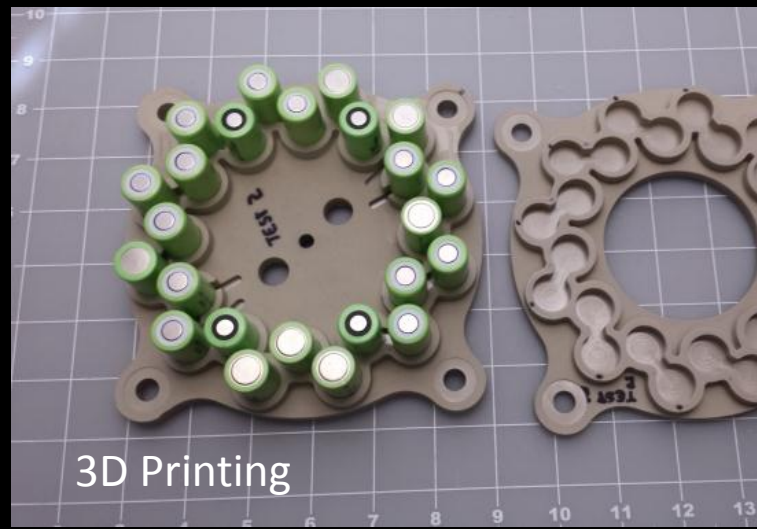


Earth Science:
Orbiting Carbon Observatory

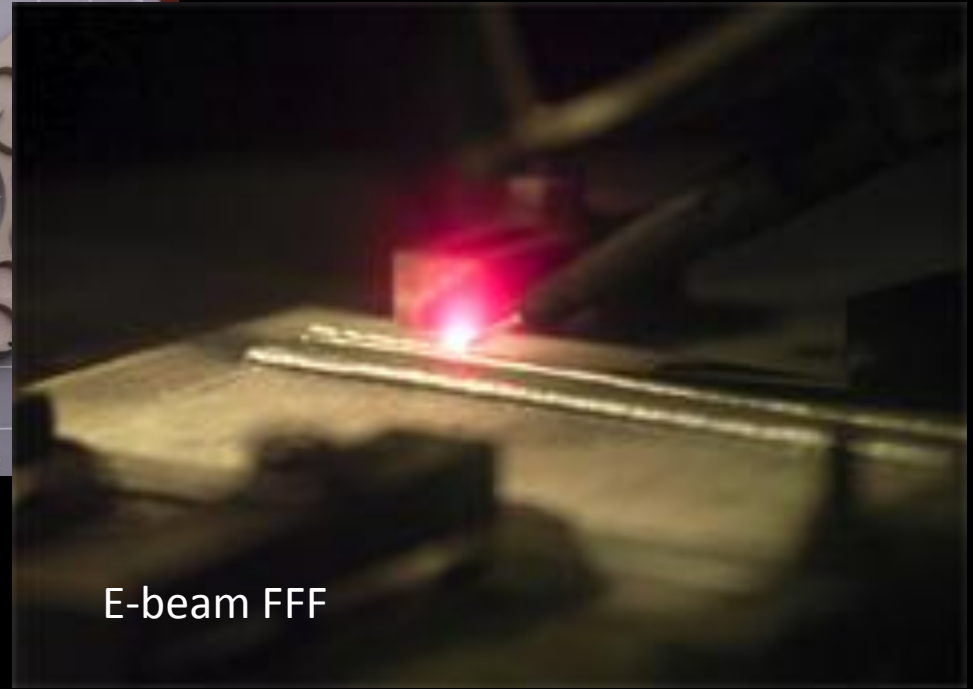


Planetary:
Cassini Image
of Saturn



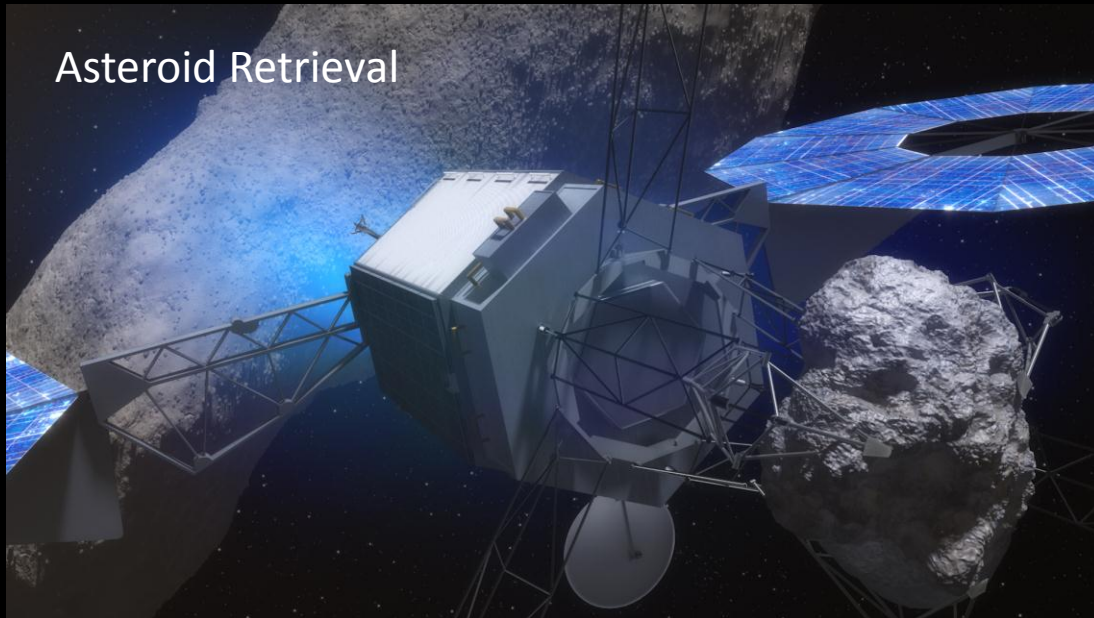


3D Printing

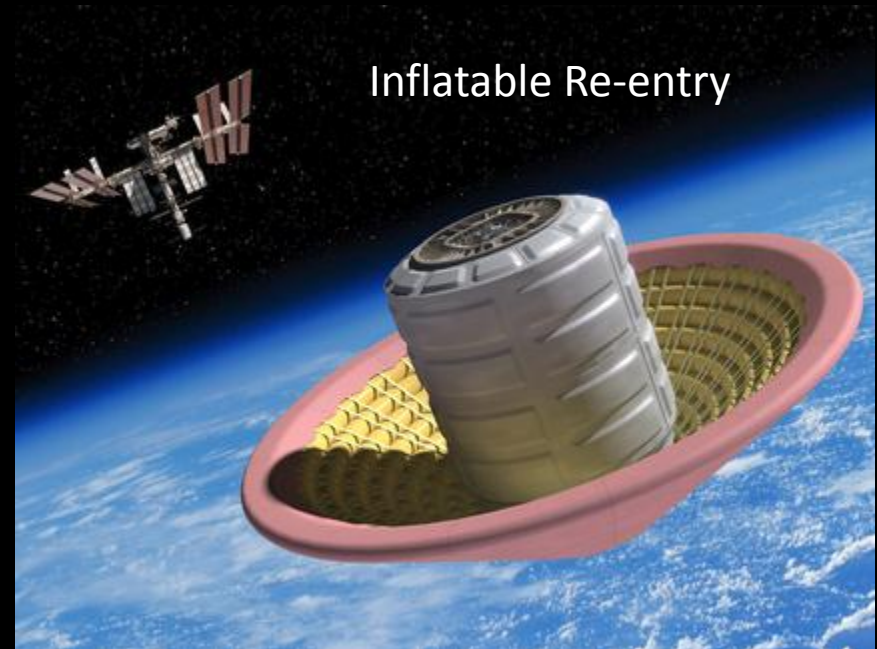


E-beam FFF

Space Technology



Asteroid Retrieval



Inflatable Re-entry



NESB

Nondestructive Evaluation Sciences Branch

- NASA
- **NESB**
- Need for composites NDE
- NESB Research
- Conclusion

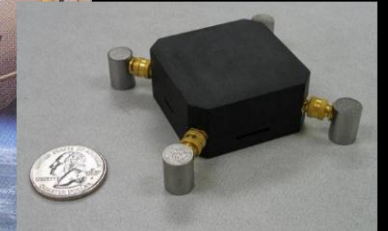
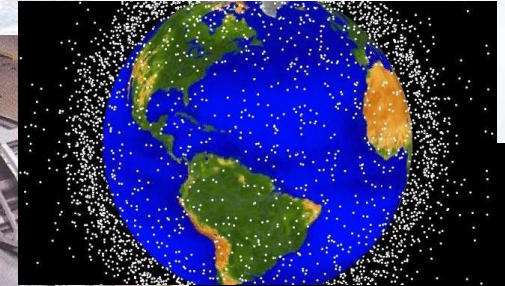
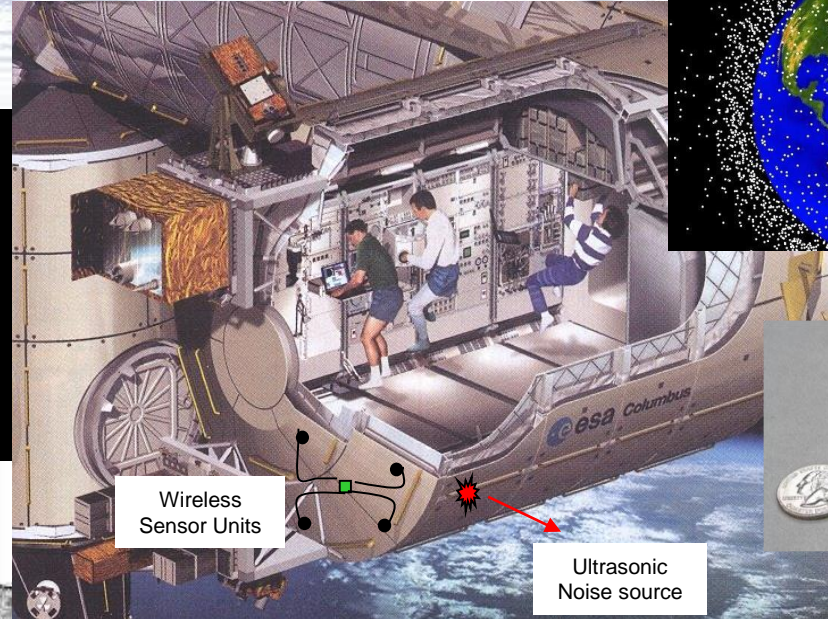
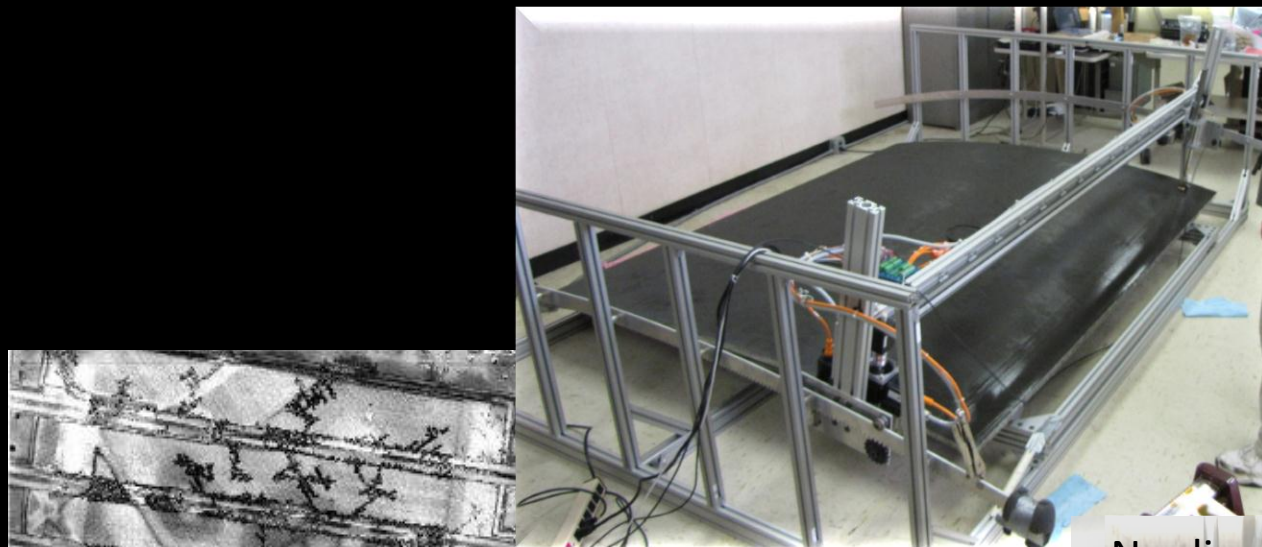
- Only branch level NDE at NASA
- 1 of 2 NDE research level organizations in the US government
- ~24 Full-Time Personnel
 - 18 Civil Servants
 - 9 Support Contractors
- Extensive Skill Mix
 - 10 PhD's
 - 65% Physicist
 - 15% Electrical Engineers
 - 15% Mechanical Engineers
 - 5% Aerospace Engineers

- NDE Research Laboratory
 - Thermal Imaging
 - Ultrasonic Scanning
 - Phased-Array Ultrasound
 - Electromagnetics
 - Computed X-Ray Tomography
 - Photo & Thermal Elasticity
 - Scanning Electron Microscopy
 - Terahertz Imaging
 - Fiber Optic Sensors Fab.
 - Nano & Mems Sensor Fab
 - Raman Spectroscopy

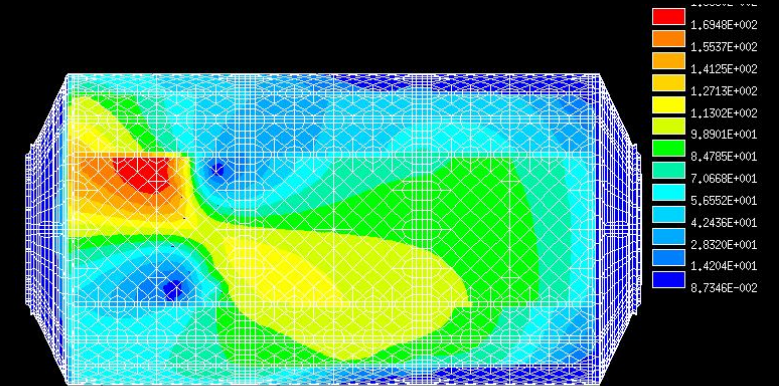
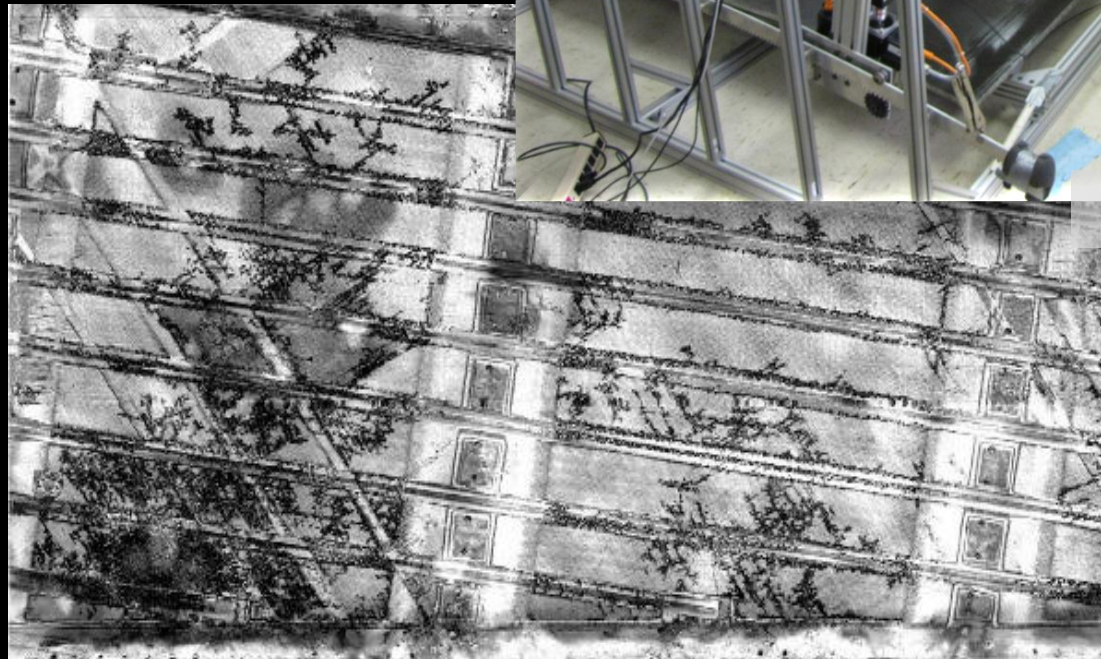


Ultrasound

Nondestructive Evaluation Sciences Branch



Nonlinear Acoustics





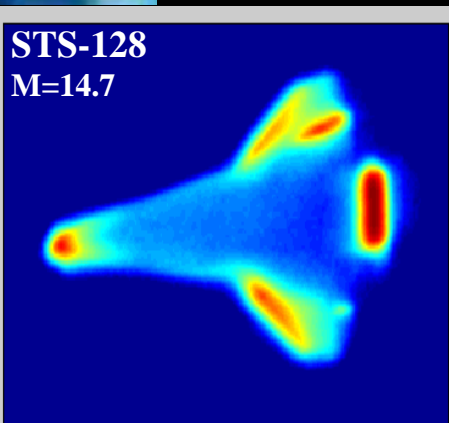
Thermography

Nondestructive Evaluation Sciences Branch

Human
spaceflight



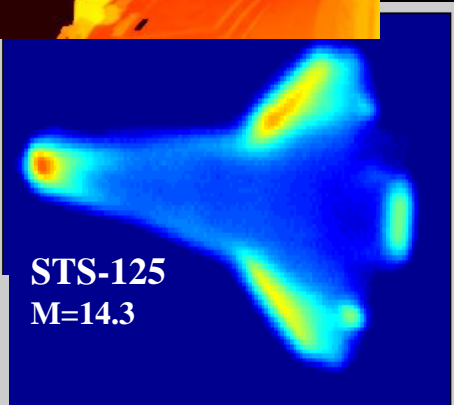
STS-128
M=14.7



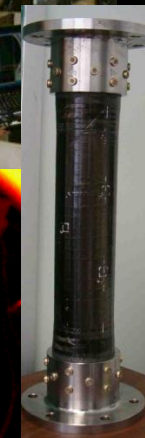
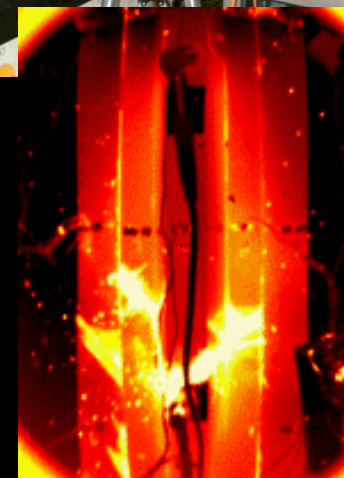
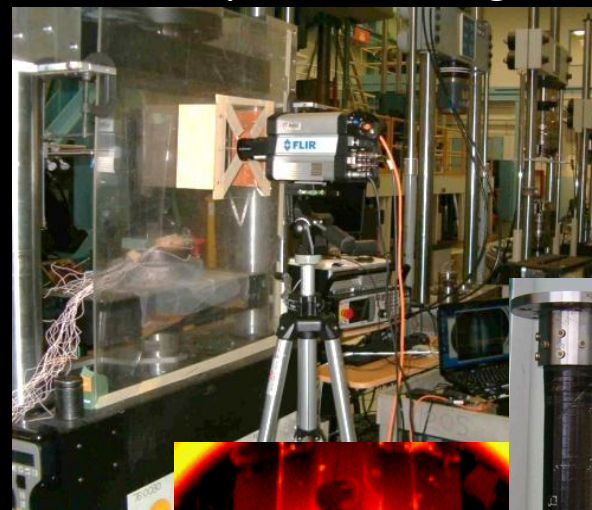
ISS Radiator



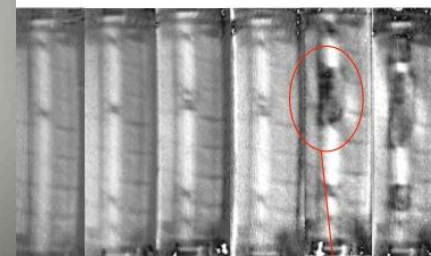
STS-125
M=14.3



Real time inspection during loading



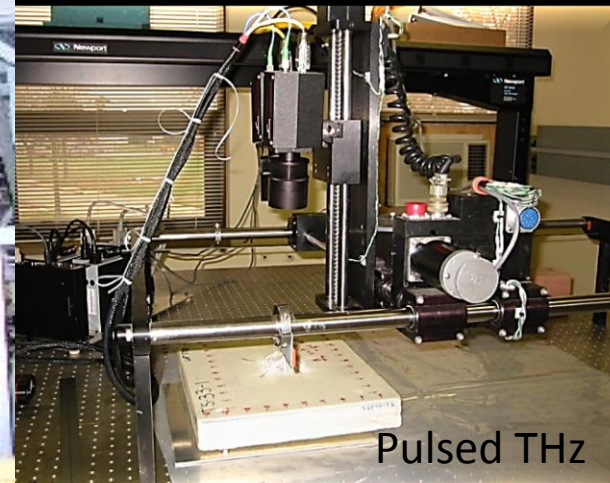
Cycles





Terahertz

Nondestructive Evaluation Sciences Branch

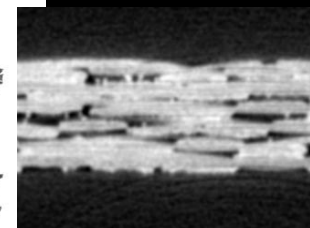
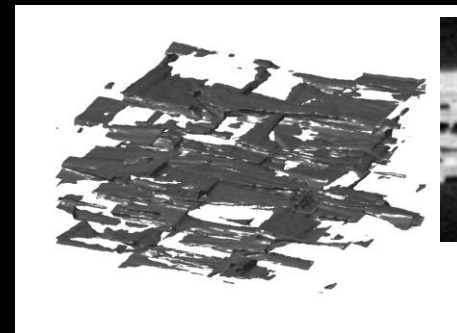
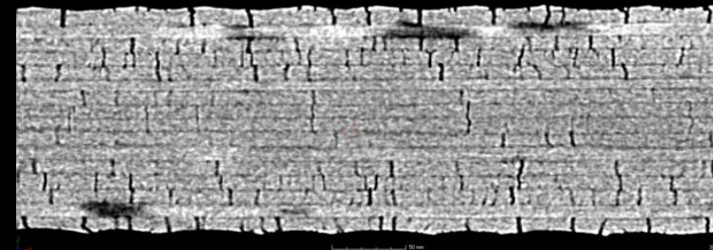
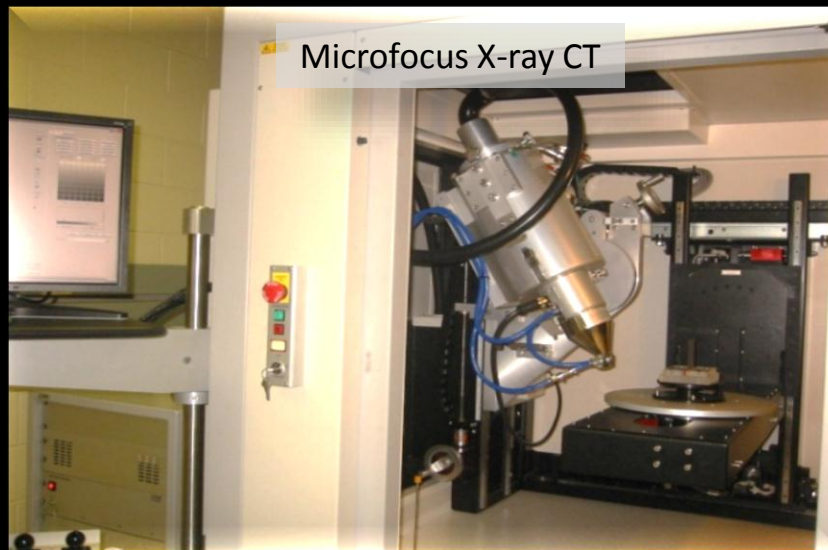
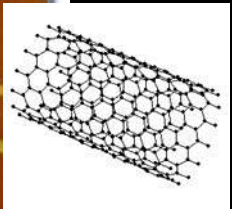
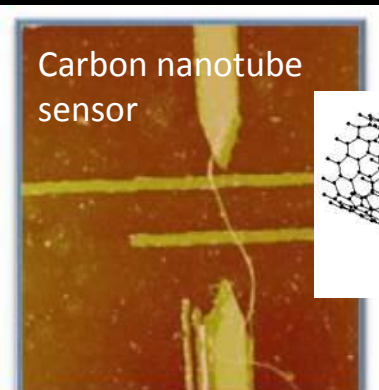


Pulsed THz

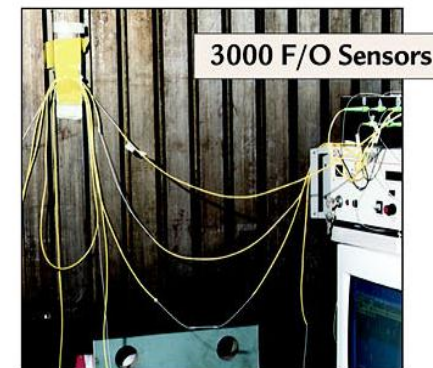
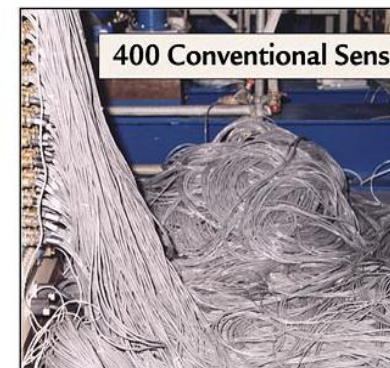
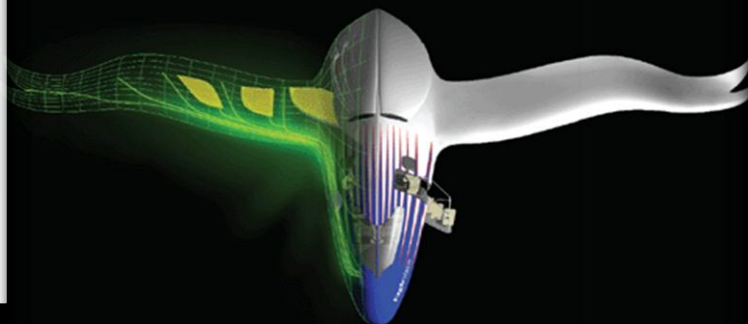
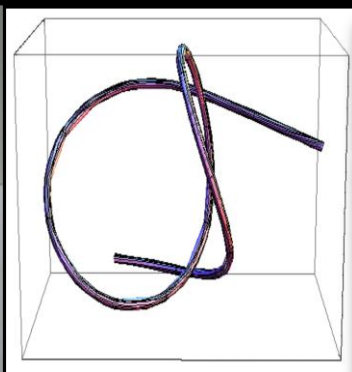


Many other areas

Nondestructive Evaluation Sciences Branch



Size of pore
0.51 mm x 0.12 mm

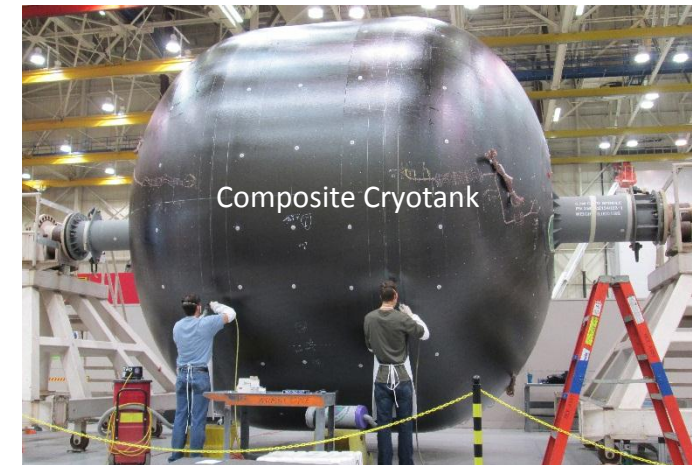
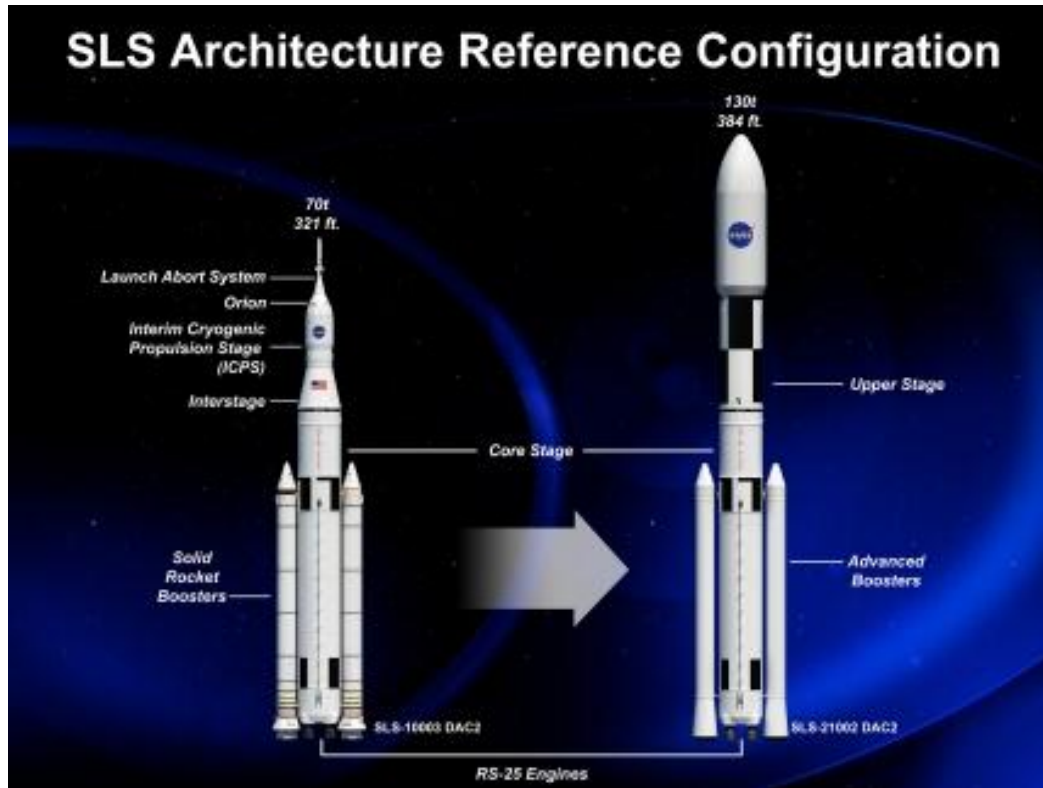




Composites in Aerospace

Nondestructive Evaluation Sciences Branch

- NASA
- NESB
- **Need for composites NDE**
- NESB Research
- Conclusion





Nondestructive Evaluation Sciences Branch

Advanced Composites Project

- 5 Year Project:
 - Reduce timeline for certification of composite structures
 - Currently takes ~20 years from material development to market use
 - Infuse advanced tools to accelerate regulatory acceptance of advanced composites
- Partnership: NASA, FAA, DoD, Industry, University
- NDE of composites will play a key role in all three technical challenge areas:
 1. Predictive capabilities (e.g., damage progression)
 2. **Rapid Inspection**
 3. Enhanced Manufacturing



GE Genx



Airbus
A-350 XWB



Bombardier
C-Series



Lockheed Martin F-35



Northrop Grumman
Fire Scout

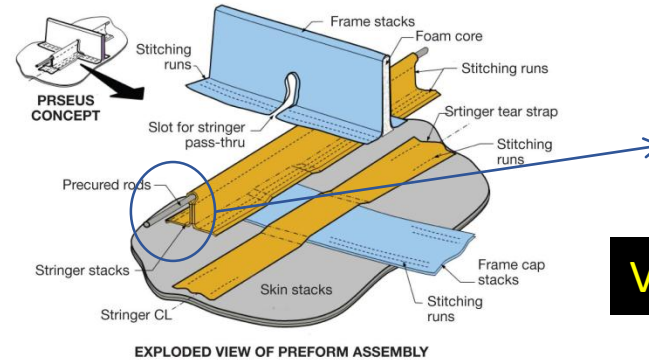
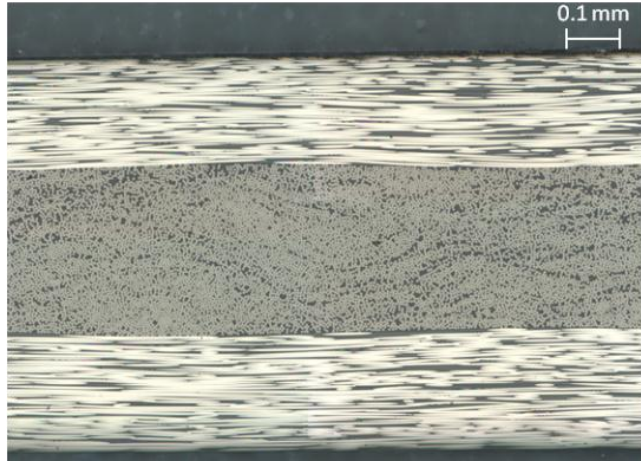


Sukhoi Superjet 100
(Russia)

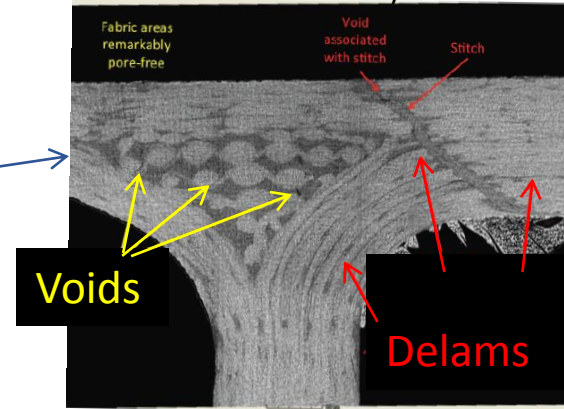




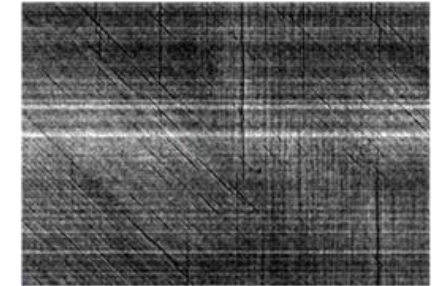
Unique Damage Types



X-ray CT of PRSEUS Joint, From NASA TM-2013-217799 by Patrick Johnston



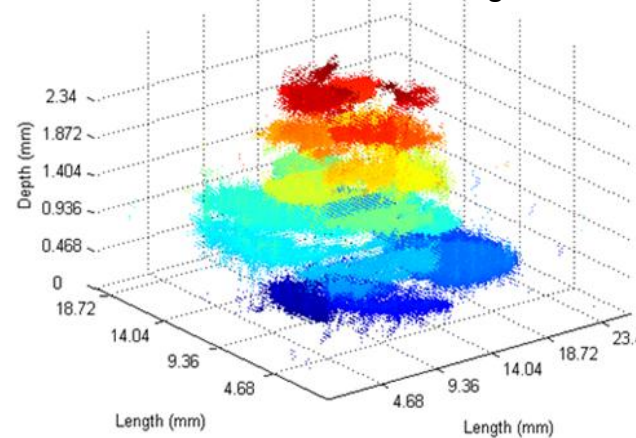
X-ray CT data of microcrack damage



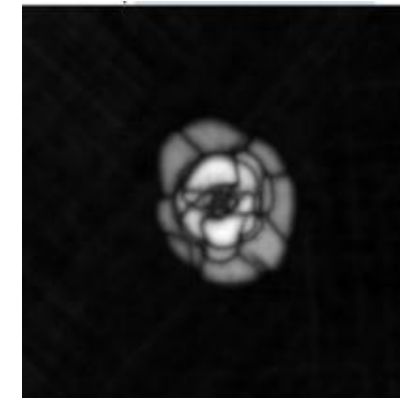
X-ray CT data of microcrack damage

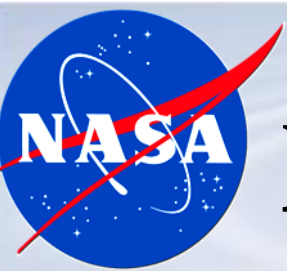


X-ray CT data of delamination damage



UT data of delamination damage





NESB Composite NDE Research

Nondestructive Evaluation Sciences Branch

- NASA
- NESB
- Need for composites NDE
- NESB Research
- Conclusion

- Focus areas: Inspection of complex geometry components and rapid large area inspection
- Development of new techniques
 - Goal: quantitative damage/material characterization
 - Microcracking, fiber waviness, delamination, porosity
- Validation of detectability
 - Inspectability of complex components
 - Model based validation tools
- Experiment:
 - Thermography, ultrasound, nonlinear ultrasound
- Simulation:
 - Custom code, 3D simulation

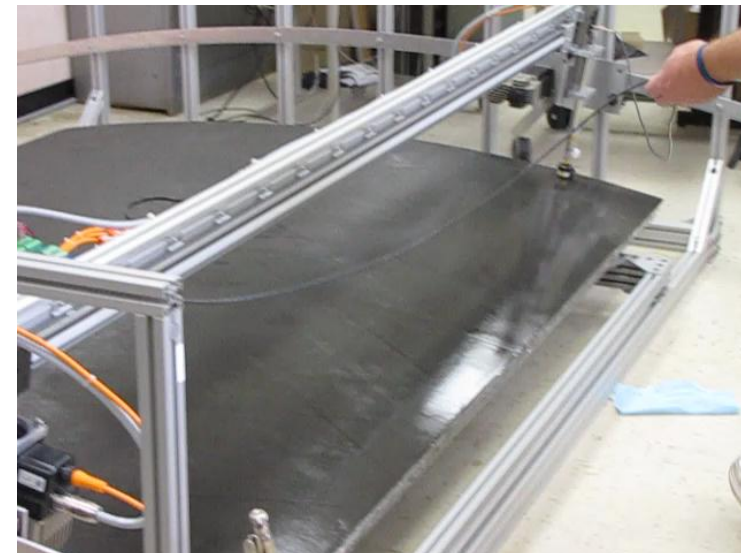




Large Area Inspection

Nondestructive Evaluation Sciences Branch

- Flash Thermography
 - Delaminations, disbonding, porosity, skin-to-core disbonding
 - Good for solid laminates and for honeycomb
 - Fast – 0.09 m^2 (140 in.^2) in 10-15 sec.
 - Can handle complex geometries
- Non-Immersion Single Element UT
 - Delaminations, disbonding, porosity, matrix cracking, core crushing, skin-to-core disbonding
 - Good for solid laminates and for honeycomb
 - Very high spatial resolution $\sim .01 \text{ in.}$ (0.25 mm)
 - Very high speed – 10-12 in. / sec.

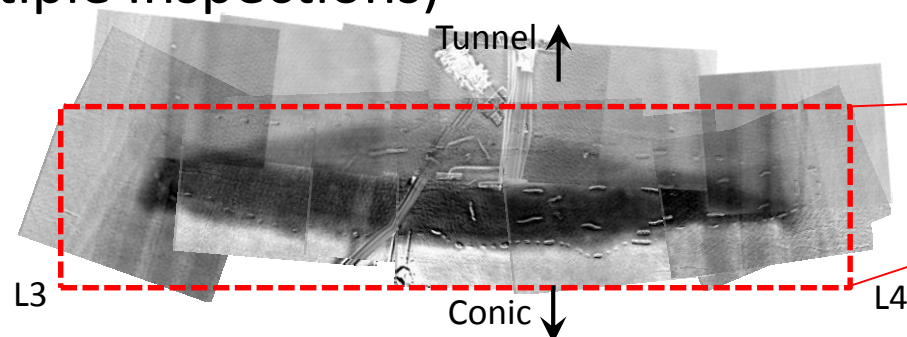




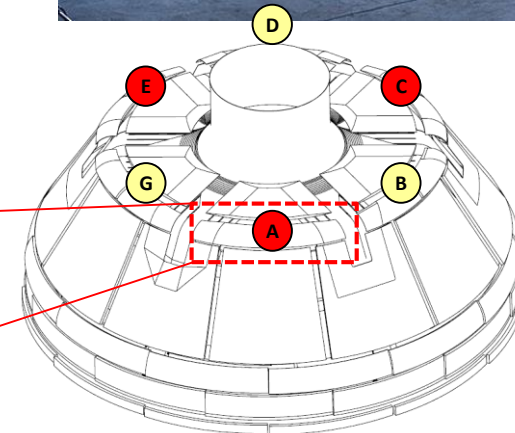
Composite Crew Module

Nondestructive Evaluation Sciences Branch

- Vessel dimensions
 - 3.8m dia. and 3.1m tall
- Full Scale Load testing to failure
- 100% Thermography
- Critical Locations UT
- AE During Loading
- ~ 140 GB of Thermal Data Acquired During Load Testing Cycle (Multiple Inspections)



LaRC PCA-processed IR image





SLS Composite Payload Fairing

1/16 Circumference

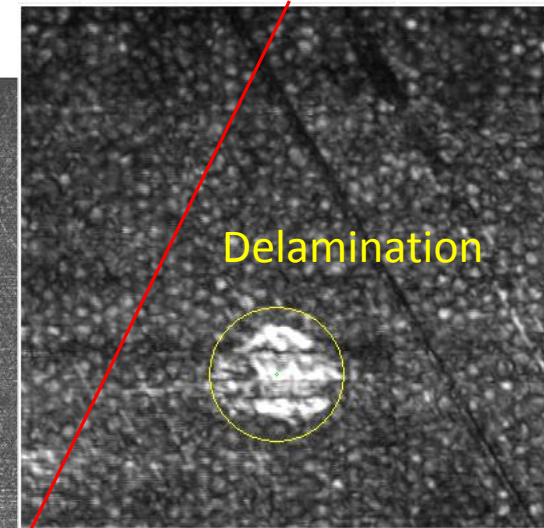
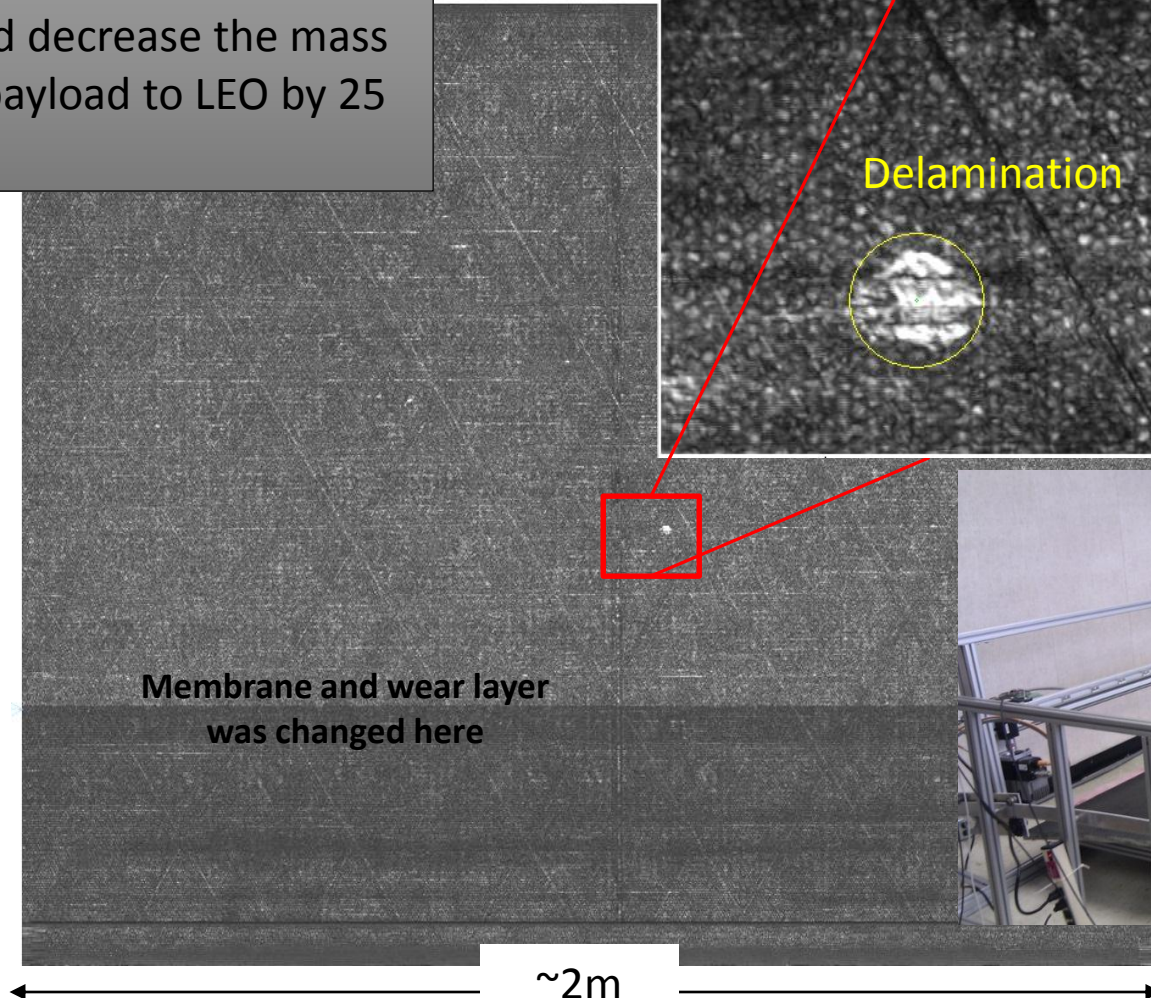
Nondestructive Evaluation Sciences Branch

SLS system trade studies show that an all composite structure would decrease the mass by 40% and increase the payload to LEO by 25 metric tons.



Payload Shroud
8.4 m Dia.

~3m



*Up to 190 GB
of ultrasonic
data per panel

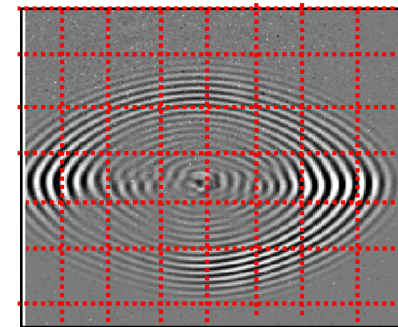
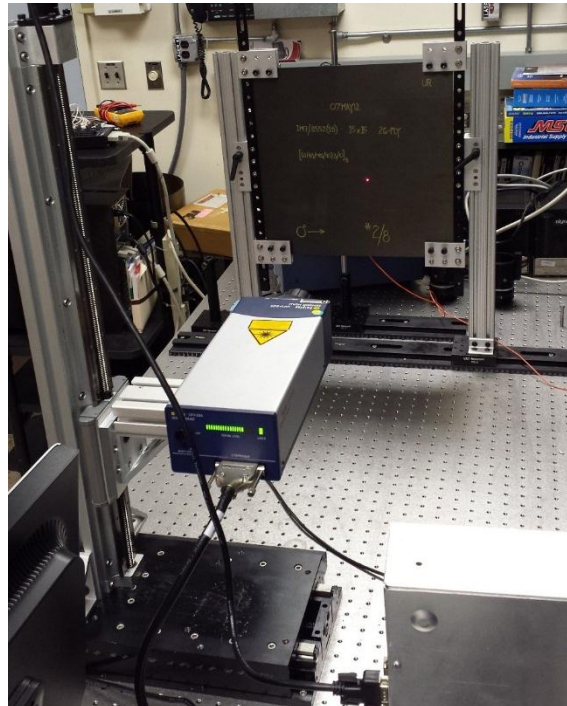
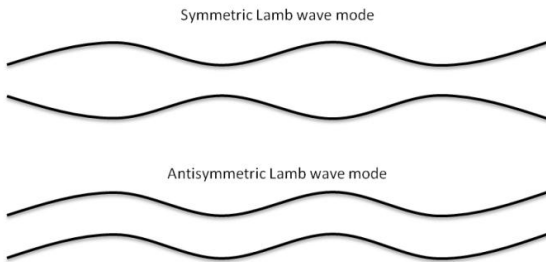




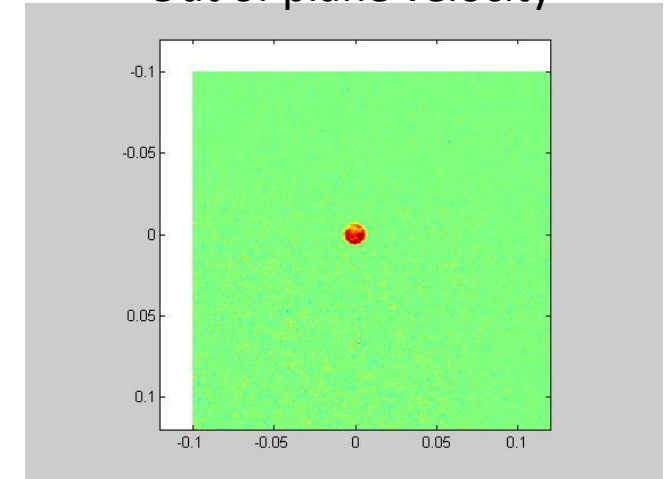
Guided Wave Ultrasound Research

Nondestructive Evaluation Sciences Branch

- GW created in plate-like specimens due to boundaries
 - Interaction of coupled L and SV with boundaries leads to various modes
- Promise for covering large areas via long distance travel
- Noncontact measurement with Laser Doppler Vibrometry



Out of plane velocity

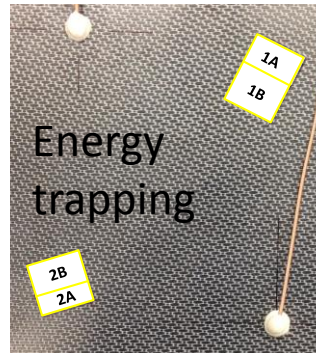
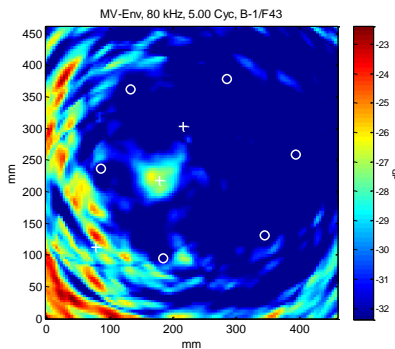
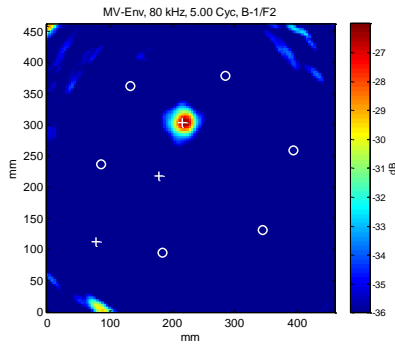




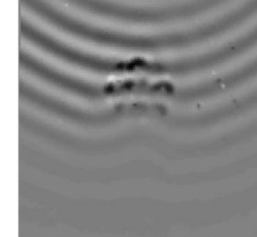
Wavefield Analysis

Nondestructive Evaluation Sciences Branch

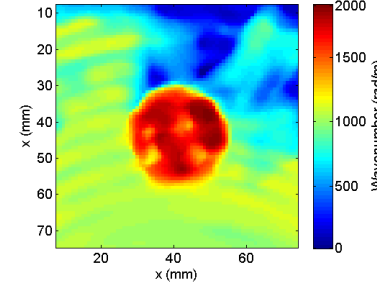
- NASA/Georgia Institute of Technology NRA starting 01/2013
 - Hybrid SHM/NDE topic: SGWA and AWI to locate *and characterize* damage
- Simulation work led to understanding of energy trapping effect on SGWA
- Moving on to test methods in complex composite components



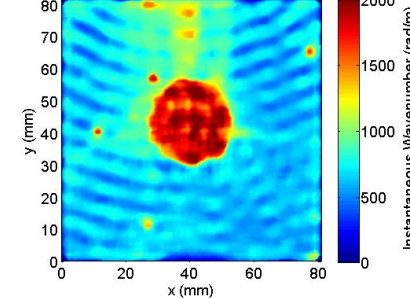
GIT Experimental wavefield data



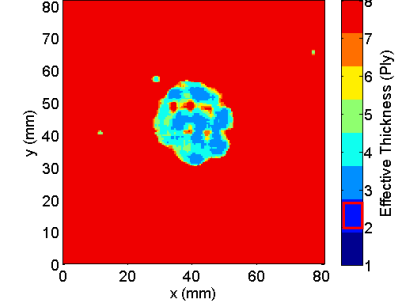
NASA local wavenumber



GIT Instantaneous wavenumber



Damage depth wave IW

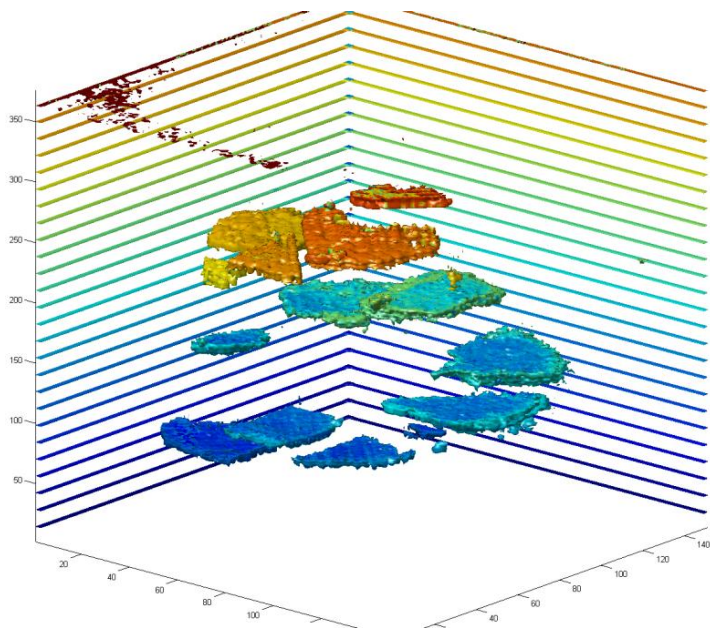




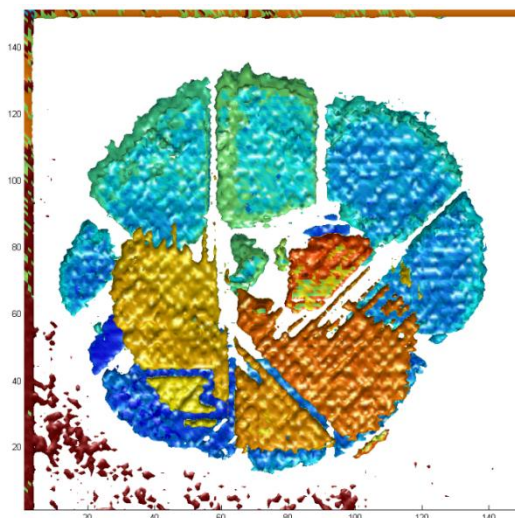
Wavenumber Analysis

Nondestructive Evaluation Sciences Branch

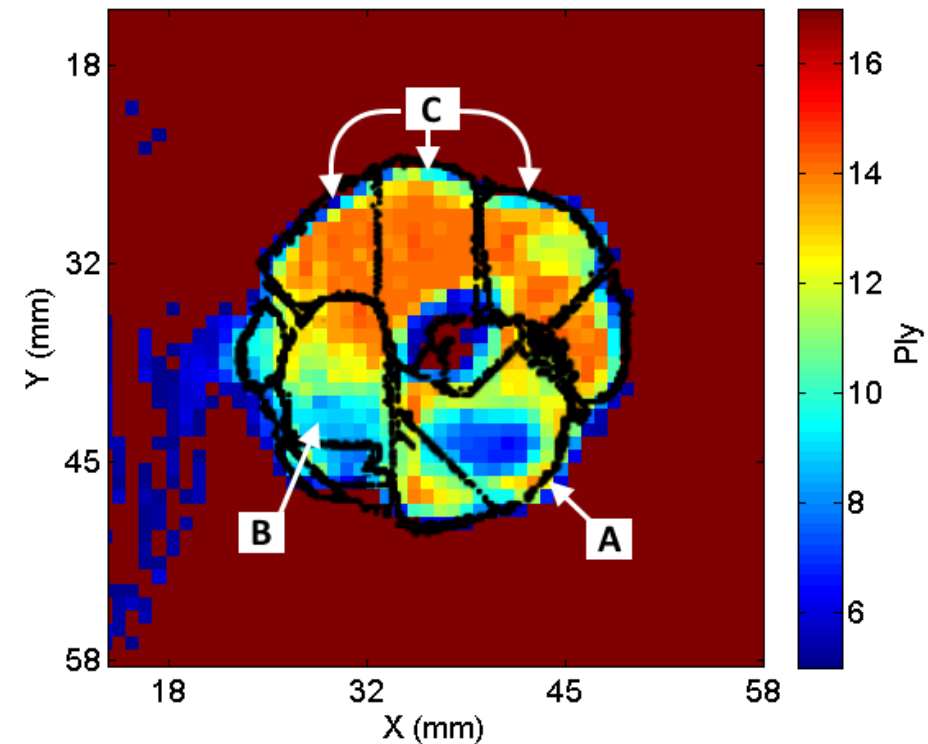
Immersion Ultrasound



Immersion Ultrasound



Noncontact LDV Wavenumber Analysis



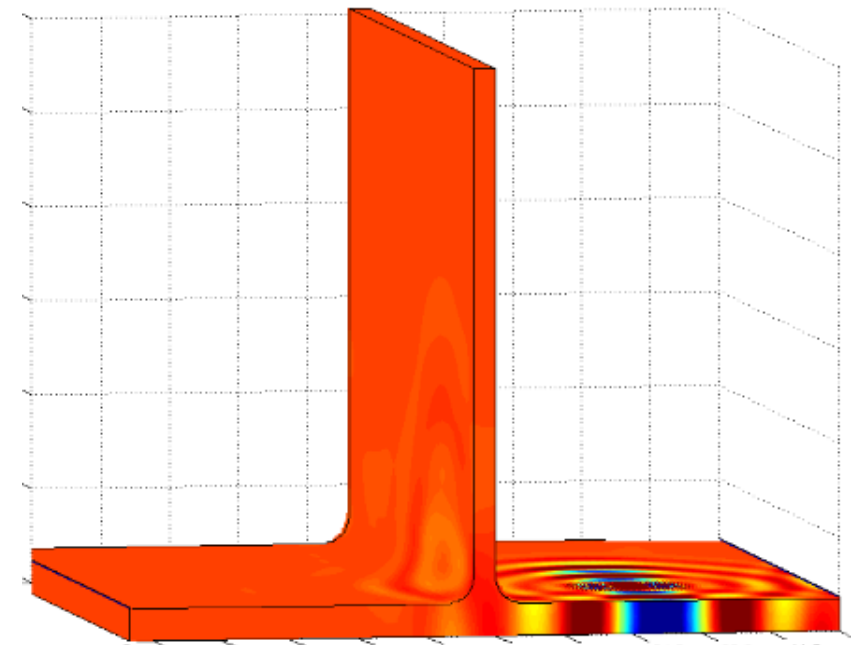
¹ Juarez, P. and Leckey, C. "Multi-frequency Local Wavenumber Analysis and Ply Correlation of Delamination Damage". *Submitted to Ultrasonics*



NDE/SHM Simulation

- NASA
- NESB
- NDE for Composites
- **NDE Simulation**
- Conclusion

- Simulation of energy interaction with material/structure and damage
 - **Composite focus**
- Realistic NDE simulation tools for aerospace materials enables inspection prediction
 - Establish confidence in ability to inspect: complex components, 'hard to reach' locations, cover large areas, advanced materials (composites)
- Creates cost-effective tools for developing and optimizing *damage characterization* techniques
- Aid in understanding of experimental results
- Simulations enable cost-effective SHM validation

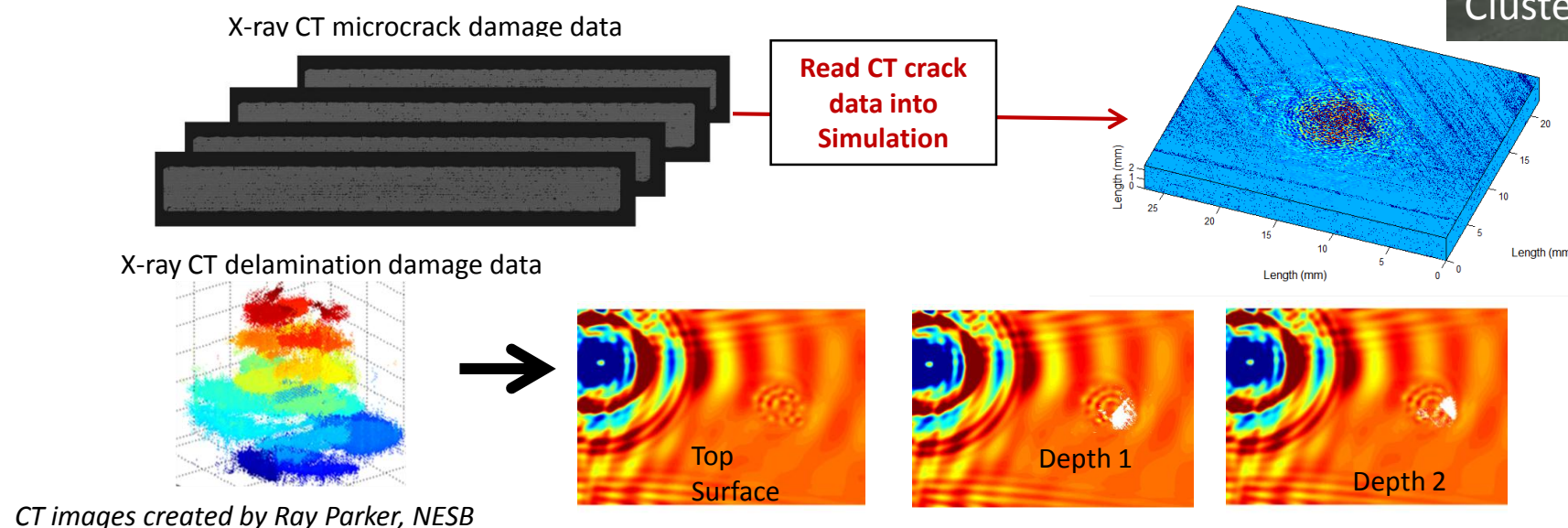




NESB Custom Simulation Code

Nondestructive Evaluation Sciences Branch

- Custom code simulates 3D wave interaction with *realistic* damage
- Custom EFIT code has many benefits:
 - Speed, memory efficiency, control, adaptability
 - Currently runs on multi-core and cluster computers
 - **Validated against experiment and theory**



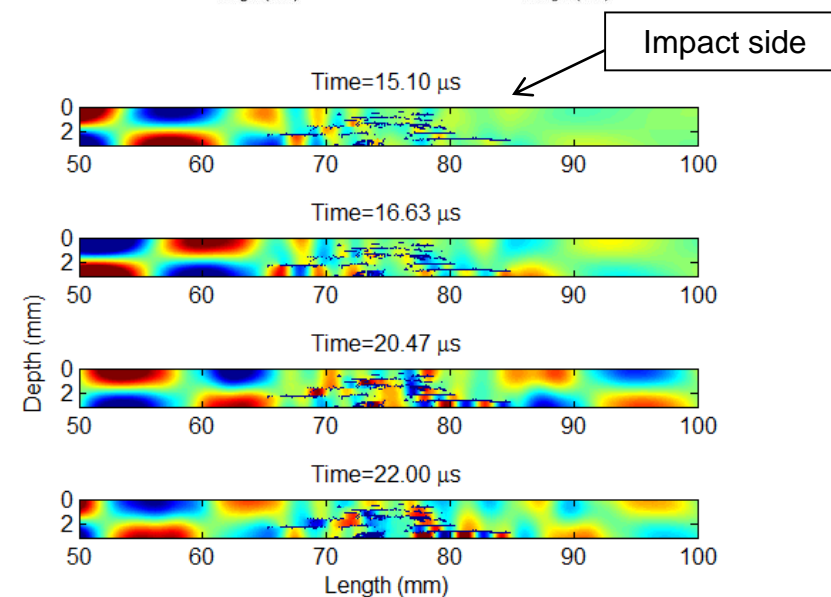
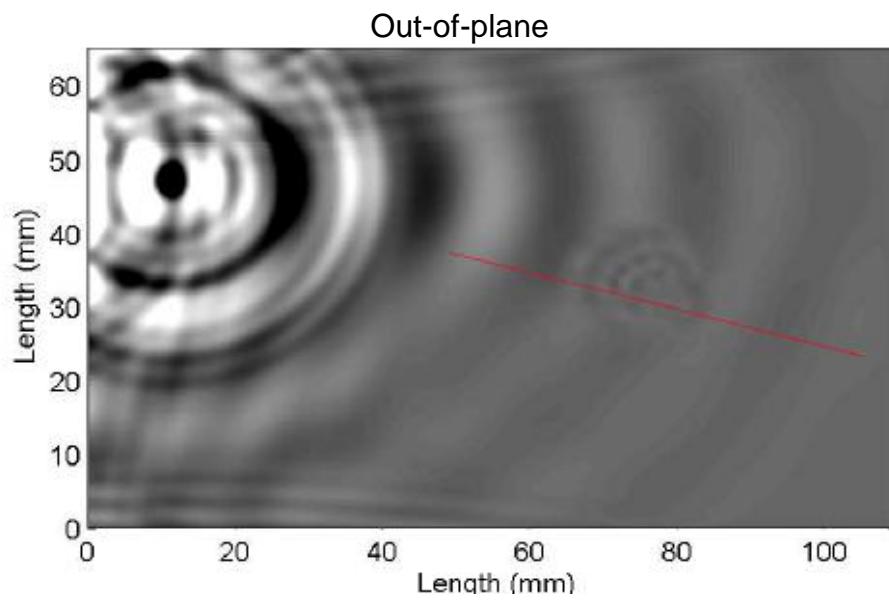
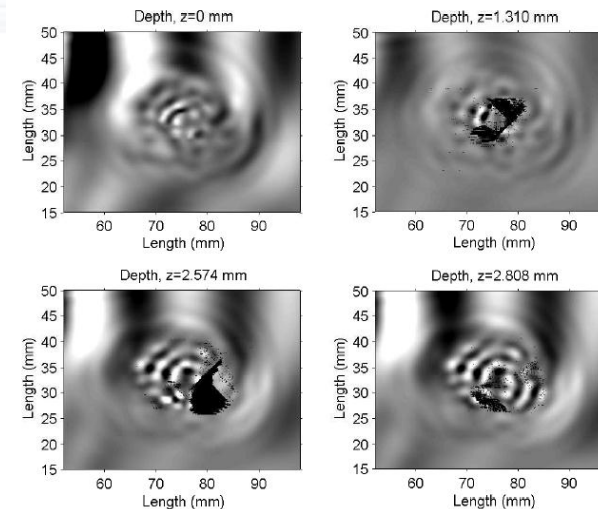
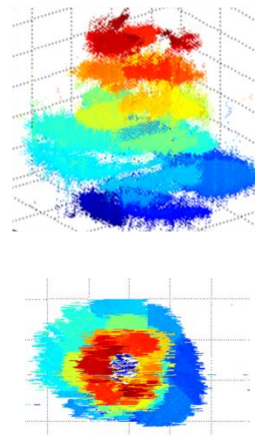
Leckey, Cara AC, Rogge, Matthew and Parker, F. Raymond. "Guided waves in anisotropic and quasi-isotropic aerospace composites: Three-dimensional simulation and experiment." *Ultrasonics* 54.1 (2014): 385-394.



Guided Wave Example

Nondestructive Evaluation Sciences Branch

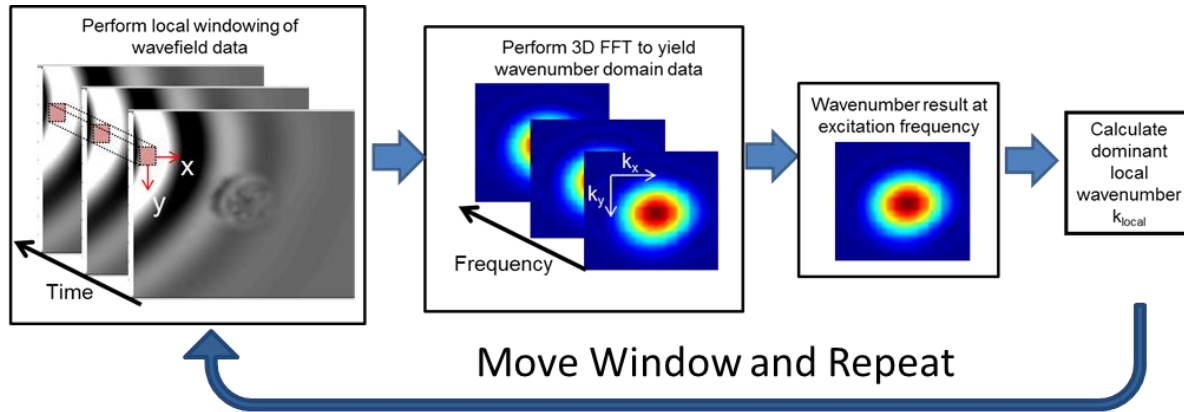
- 3D EFIT: 1.8 billion grid cells
 - 110 mm x 65 mm x 3.2 mm
- Run on 80 core 1TB shared memory machine
- Step size=23.4 μ m, $\lambda_{\min}/64$
- Images show shorter wavelength scattering from damage





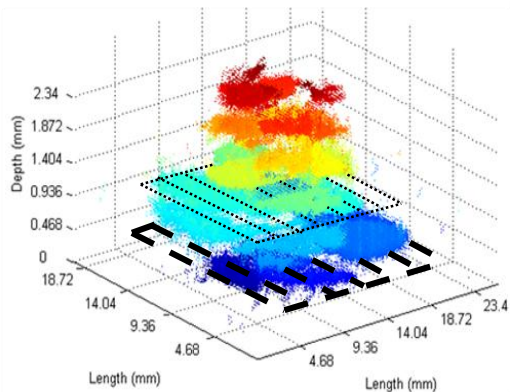
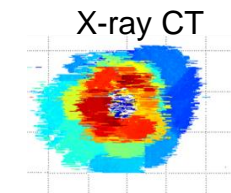
Data Processing: Wavenumber Analysis

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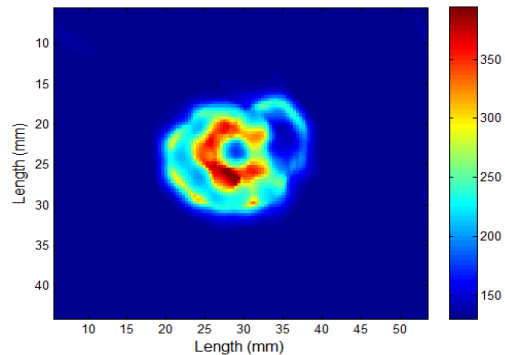


Local Wavenumber Analysis Technique:

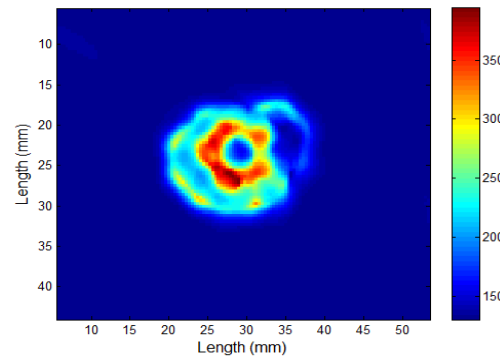
- 1) 3D FT of Hann windowed wavefield, local window
- 2) Select 3D FT slice at excitation center frequency
- 3) Calculate dominant wavenumber of local window



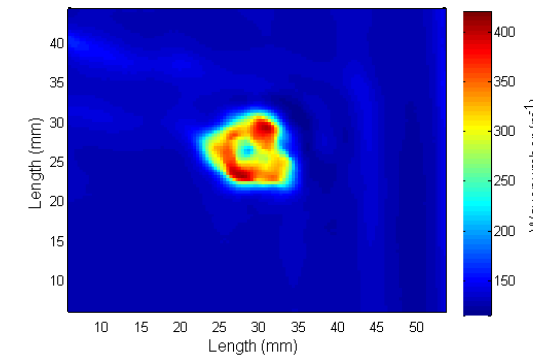
Case 1
Full delam



Case 2,
Hidden delam removed



Case 3,
Half delam removed



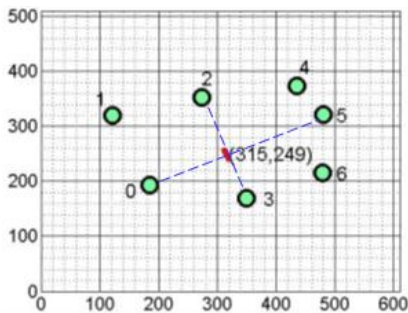
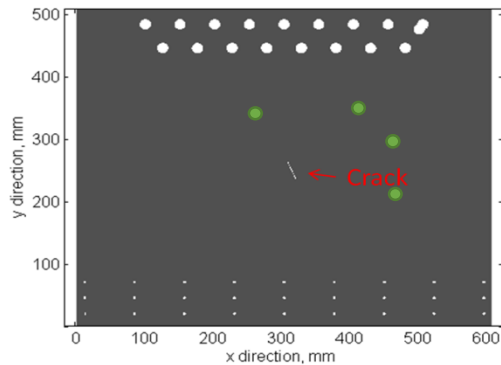
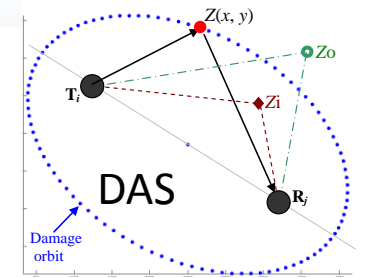
Rogge, M. and Leckey, C.; "Characterization of impact damage in composite laminates using guided wavefield imaging and local wavenumber domain analysis"; *Ultrasonics*, Vol 53, pp 1217-1226 (2013)



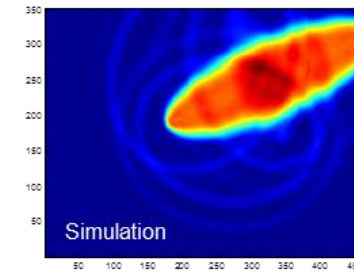
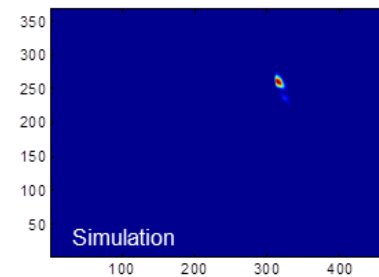
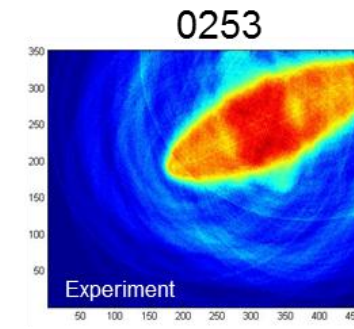
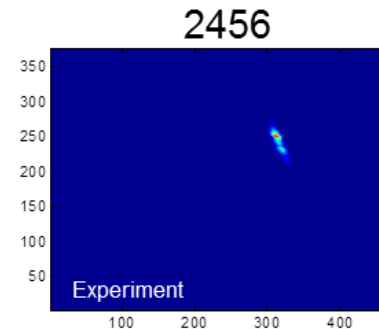
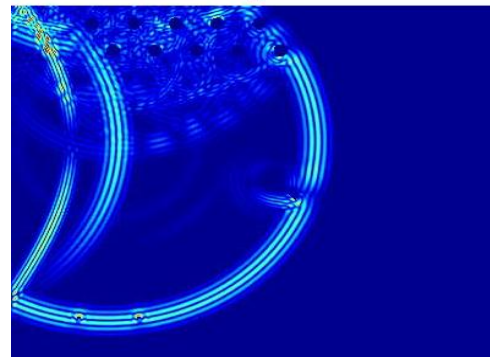
Model Based Detectability Studies

Nondestructive Evaluation Sciences Branch

- NASA/University of South Carolina*
- Started with simple isotropic (aluminum) case
- Results¹ demonstrated use of 3D simulation data in place of experimental data for investigating sensor location w.r.t. damage



Snapshot of simulated wavefield:



¹Yu, L. and Leckey, C. "Lamb Wave Based Quantitative Crack Detection using a Focusing Array Algorithm". *Journal of Intelligent Material Systems and Structures*, Vol 24, pp 1138-1152 (2013)



Conclusion

Nondestructive Evaluation Sciences Branch

- NASA needs quantitative NDE for aerospace components, including:
 - Rapid inspection for large scale parts
 - Techniques for complex geometry composites
 - Validation methodologies for determining inspectability
- Experiment and simulation are needed to develop optimized, validated inspection/monitoring techniques
- NESB is performing ongoing research in these areas

A list of related publications can be found at:

<http://nde.larc.nasa.gov/physicsbased.shtml>

Thanks to:

- Peter Juarez
- Jeffrey Seebo

QUESTIONS?

*NASA/USC work under SAA1181

**NASA/GaTech work under NRA NNX12AL13A

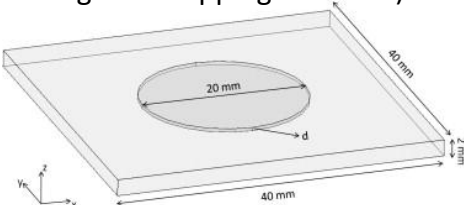


Simulation SOA and Gaps

Nondestructive Evaluation Sciences Branch

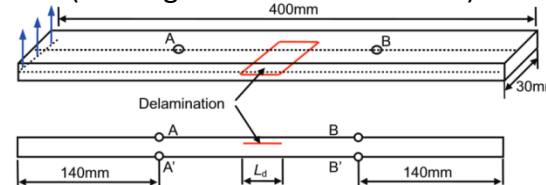
- SOA of NDE and SHM modeling/simulation *not adequate* for future needs, including:
 - Larger scale simulations
 - Composites
 - Advanced designs
 - Realistic damage scenarios

3D FE, Single circular delamination
(investigated 'clapping' behavior)



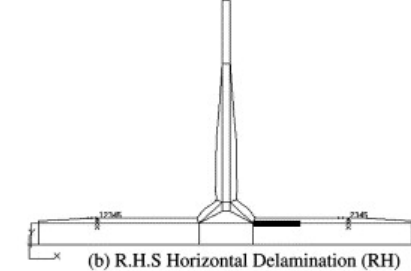
From: Delrue, Steven, and Koen Van Den Abeele. "Three-dimensional finite element simulation of closed delaminations in composite materials." *Ultrasonics* 52, pp 315-324 (2012)

3D FE, Single rectangular delamination
(investigated mode conversion)



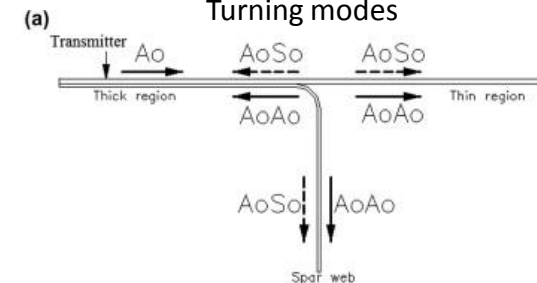
From: Liu, Zenghua, et al. "Delamination detection in composite beams using pure Lamb mode generated by air-coupled ultrasonic transducer." *Journal of Intelligent Material Systems and Structures*: 1045389X13493339. (2013)

2D FE, Single 'strip' delamination



Kesavan, A., et al. "Damage detection in T-joint composite structures." *Composite Structures* 75.1 : 313-320. (2006)

2D FE (ANSYS)
Turning modes



Ramadas, C., et al. "Interaction of Lamb mode with structural discontinuity and generation of "Turning modes" in a T-joint." *Ultrasonics* 51.5: 586-595. (2011)



Computational Trends

Nondestructive Evaluation Sciences Branch

- Computational power per unit space increasing, cost decreasing
- iPad2 has as much processing power as Cray 2 (world's fastest computer in mid 1980s)
- Cost per GFLOP (adj for inflation)
 - 1984: \$42M
 - 1997: \$42k
 - 2007: \$52
 - 2013: \$0.12
- Simulations will play an increasing role in the future science and engineering (including NDE)



NASA Cray 2 Supercomputer
NASA Langley Research Center 3/23/1989 Image # EL-2001-00428



Nondestructive Evaluation Sciences Branch

Guided Wave Simulation

